AN EVALUATION OF SOME NEW PHOTOTUBES WITH HIGH GAIN FIRST DYNODES*

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## Abstract

We have examined high gain first dynode phototubes for use in a multicell gas Cherenkov counter at Fermilab. Price and availability dictated a careful examination of the EMI9839KB. Preliminary laboratory tests followed by test beam evaluation indicated that these tubes were adequate. We report here how the best of more than sixty of these tubes were selected based on their quantum efficiency, single electron resolution, gain and noise. Using the same test procedures we then evaluated small samples of Hamamatsu R1332, Amperex PM2262 and RCA 8850 tubes. We also report pulse height resolution and pulse shape data on the Hamamatsu R1262X phototube. We conclude that all four manufacturers now produce tubes with useful single photoelectron resolution and fast time response.

## Introduction

Since 1968 when RCA began introduction of a series of photomultiplier tubes with high gain dynodes,[1] a wide variety of uses for these tubes has developed.[2] All uses center around the ability to resolve single photoelectrons from both non-cathode noise and multiphoton events, but depend in different ways on the photocathode sensitivity, fast timing properties, pulse height resolution and noise properties. Very recently, other suppliers have entered the market for these tubes.

## Requirements

We sought tubes for a 40 cell Cherenkov counter for use in particle identification in multiparticle final states.[3] Restricted path length availability limits light production and forces us to provide state-of-the-art light collection systems. We opted for bialkali photocathodes on glass envelope tubes coated with p-terphenyl wavelength shifter to achieve good quantum efficiency.[4] In order to optimize use of scarce particle beam time, we looked for tubes with which we could establish high voltage settings and maintain the resulting gain based on the single electron peak of the tubes.

## Preliminary Evaluation of EMI9839KB

Based on price and availability in 1979, we ordered twelve EMI9839KB phototubes. These tubes feature modest first dynode gain and single electron resolution,[5] bialkali photocathodes, plano-plano borosilicate glass envelopes and 12 stage BeCu linear focused dynode structure. After a series of laboratory tests (as detailed in the following pages) indicated reasonable gain, single electron resolution and good photocathode blue response, we chose to confirm the suitability of these tubes for Cherenkov counter use by test beam measurements. We therefore set up a test in the Fermilab M5 test beam which measured the light collection properties of our Cherenkov counter components and demonstrated the suitability of our laboratory tests for evaluation of Cherenkov counter phototubes.

## Beam Tests

The test apparatus is shown schematically in Figure 1. A test beam of negative 30 GeV/c particles was defined by scintillator counters U,D and Cherenkov counters $C_1$ and $C_2$. These particles were focused onto a final set of defining counters X, Y and Z where Y was a veto counter with a 2 cm circular hole. The test Cherenkov counter $C_T$ consisted of a 1.4 m long aluminum box filled with nitrogen at atmospheric pressure.[6] A 2.4 mm thick spherical glass mirror (focal length 1 m) focused light onto a Winston type light collection cone[7] placed at 90° to the beam direction. This cone collected light from a 5" diameter circle and focused it onto a 1.9" diameter circle for the photocathode.[8] The phototube to be tested was placed at the exit of this cone. A moveable baffle was placed upstream of the mirror to allow tests with light collection from various particle path lengths.

## Test Procedure

The beam Cherenkov counters $C_1$ and $C_2$ were set to define electrons by appropriate helium pressure. Using coincidence circuits, we defined particles incident on the test counter $C_T$ by $UDC_1C_2X\overline{Y}Z$=E for electrons and $UD\overline{C_1}\,\overline{C_2}X\overline{Y}Z$=H for non-electrons (mostly $\pi$). Since both pions and electrons are well above threshold in $N_2$ at this momentum, tests could be performed with each. H defined a high rate beam but with a small admixture of slow particles. E contained an (almost) pure fast electron beam but at lower rate. We used the inefficiency method to determine the photoelectron statistics. For a given baffle setting and using a 30mV threshold on $C_T$, we varied the voltage on the test tube to

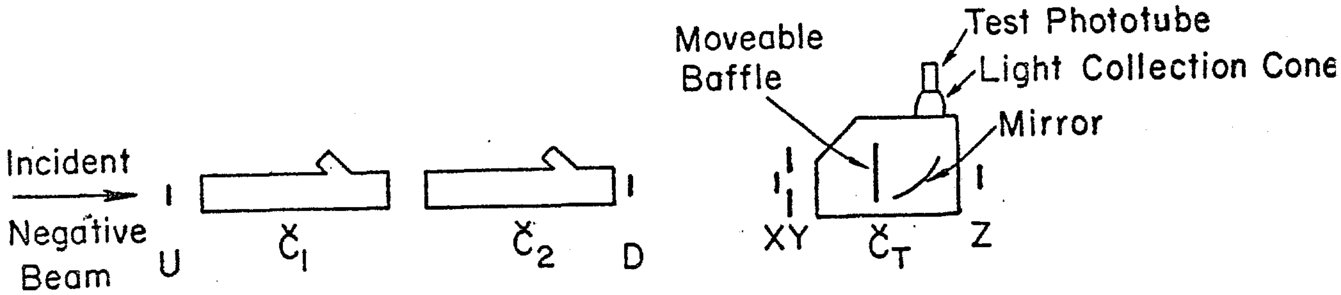



Fig. 1. Cherenkov Test Counter configuration at Fermilab M5 beam. The baffle can be moved parallel to the particle path to vary the length from which photons are collected.

maximize the efficiency, $\varepsilon_H$, of $C_T$ (plateau) where

$$\varepsilon_H = \frac{C_T \cdot H}{H}.$$

We then varied the baffle location and recorded for each path length $\ell$ the efficiency $\varepsilon_H$ as well as the accidental rate associated with it, $a_H$ (as measured with 200 ns delay). Each tube was measured in this fashion. Then a sample of 6 tubes was coated by vacuum deposition with p-terphenyl followed by $MgF_2$ for protection. The measurement of efficiency vs. path length was then repeated.[9]

## Analysis of Test Beam Measurements

We write the formula for light production in a Cherenkov counter as:

$$N = N_o\ \ell\ \sin^2\Theta_c \cong N_o\ \ell\ 2(n-1),$$

where N is the observed number of photoelectrons for a single fast particle, $\ell$ is the path length for which we collect light from the beam, $\Theta_c$ is the Cherenkov angle, n the index of refraction of the gas and $N_o$ is a figure of merit for the light collection system. $N_o$ involves an integral over wavelength of the Cherenkov production spectrum, transmission of light in the gas, the reflectivity of the mirror, the absorption and emission properties of the wavelength shifter (if any) and the quantum efficiency of the photocathode. The second expression holds for particles well above threshold. By determining N vs. $\ell$ we infer $N_o$ for our system.

If we assume that each photoelectron emitted causes a count in the tube then we can relate the probability of no count (p) to the number of photoelectrons by Poisson statistics,

$$N = -\ln (p)$$

We found however that with suitably long path lengths, the efficiency did not rise sufficiently close to 1. This could be naturally attributed to the combination of false counts in the beam telescope H and to counts due to slow particles ($\bar{p}$ plus off-momentum secondaries). With sufficient data on $\varepsilon_H$ vs. $\ell$, this could be adequately accounted for by assuming a maximum efficiency $\eta_H$ corresponding to $C_T$ counting all fast particles. Taking this and accidental rates into account we find that

$$N = -\ln\left(1 - \frac{\varepsilon_H - a_H}{\eta_H(1-a_H)}\right).$$

TABLE I

Test Beam and Laboratory Measurements on EMI9839KB

| Tube # | Results without p-T $N_o$ | $\eta_H$ | Results with p-T $N_o$ | $\eta_H$ | FNAL "CB" | EMI CB |
|---|---|---|---|---|---|---|
| 75308 | 61 | .99 | 130 | .99 | 11.9 | 10.6 |
| 75309 | 62 | .99 | 124 | .994 | 11.3 | 10.6 |
| 75313 | 65 | .98 | 135 | .991 | 11.9 | 10.3 |
| 75318 | 67 | .99 | 172 | .998 | 11.7 | 12.2 |
| 70475 | 25 | .98 | 78 | .99 | 7.2 | 5.8 |
| 70479 | 33 | .99 | 75 | 1.0 | 6.5 | 5.3 |

**NOTE**: FNAL "CB" numbers are unnormalized. Average $N_o$ for uncoated tubes is 52. Average $N_o$ for coated tubes is 119. So the wavelength shifter gains on average 2.3. Average EMI CB is 9.15. If CB is selected to be greater than 10, expect $N_o$ with coated tubes to be > 130.

To determine $\eta_H$, we require a linear relation between $\ell$ and N. In Figure 2, we plot the calculated values of N for various assumptions of $\eta_H$ for a typical data set. The value of $N_o$ shown is calculated from the solid line corresponding to $\eta_H$=.988. Note that at low efficiencies (short path length) there was less effect from $\eta_H$ so that one could obtain a lower limit on $N_o$ without further assumptions using short path length data.

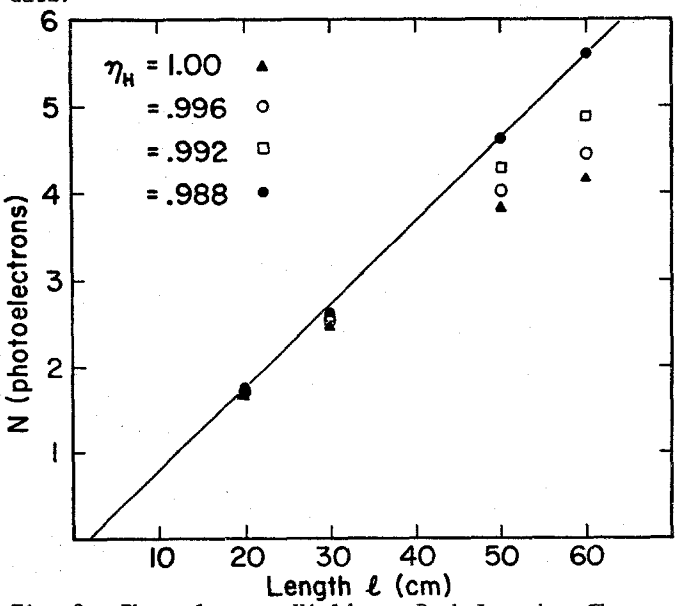



Fig. 2. Photoelectron Yield vs. Path Length. The line corresponds to $N_o$=172. The beam contamination is characterized by $\eta_H$. See text.

## Results from Test Beam

In Table I, we list our test results for various tubes with and without wavelength shifter and also the results of both Fermilab and EMI laboratory tests for these tubes. Based on this table, we draw several important conclusions:

1. The laboratory tests of photocathode response are in good agreement with the beam tests. Useful selection can be made on the tubes in the lab.

2. With our light collection system we have obtained an average improvement of a factor of 2.3 in $N_o$ by use of the wavelength shifter p-terphenyl.

3. We can obtain values $N_o$>130 by appropriate selection from a sample of EMI9839KB phototubes.

## Laboratory Tests

During the summer of 1980, we assembled test equipment, bases and tubes to allow selection of the best tubes from a sample of sixty-seven EMI9839KB tubes. With this equipment, we have tested also the RCA, Hamamatsu and Amperex tubes listed previously.

## Pulse Shape Measurement

We used a base which had been carefully configured to eliminate ringing effects due to external connections. We placed tube and base in a dark box and supplied sufficient voltage to see pulses from photocathode dark current. (With all of these tubes this provides a distinctive pulse height band.) This was recorded on a Tektronix 7904 Oscilloscope triggered internally (to provide pulse shape information independent of photocathode transit times and light source pulse effects).

Photocathode Sensitivity Measurement

We constructed for each tube to be tested a base which connected the tube as a photodiode with all dynodes and grids connected to the anode. This was then connected to the phototube and the full cathode exposed to a stable light source. The light source[10] used was a 1B59/1130B glow discharge tube powered by a stable 60Hz square wave generator. Filters were interposed between source and photocathode to define the frequency band to be measured. For measurements of blue response a Corning CS-5-58 filter[11] of half stock thickness was chosen. This was intended to approximately reproduce the relative response of the CB number defined by EMI[12] and others. For purple response near the emission peak of the p-terphenyl[13] we chose a Corning CS-7-37 filter.[11] The phototube output was connected to the 1 Megohm input of a Tektronix 575 Oscilloscope. The output voltage on the scope is then directly related to the photocathode response at the wavelength given. Using a fixed source light level, all tubes were compared for both blue response (defined CB) and near ultraviolet response (defined CP). These provide a relative measure of photocathode response.

Gain Measurements

The phototube gain was obtained by calibration of the pulse height analysis system from which we obtain the charge in the single photoelectron peak.[14]

Single Electron Resolution Measurements

The resolution of the tubes for single and multiple photoelectrons was measured with a Northern NS-900 multichannel analyzer driven by a EG&G LG102/N linear gate and stretcher. The light source was a green light emitting diode (LED) driven by a 30ns wide pulse. A 150ns pulse was derived from the pulser and gated the LG102/N. This system operates at > 20 KHz allowing very rapid data acquisition. The disadvantage lies in the fact that multi-photoelectron events do not come from simultaneous photoelectrons so any instantaneous current effects on multiphoton resolution will be missed. We measured resolution with a peak 25 channels above pedestal which corresponds to a gain of $(7 \pm 3) \times 10^6$.

Noise Rate Measurement

The rate of noise pulses was measured by amplifying the anode pulse in a X10 fast amplifier (LRS 234) and discriminating the resulting pulse at a 30mV threshold with a LRS 621BL discriminator whose output drove a fast scaler. The gain was set at 25 ch above pedestal as described above. We determined the threshold for this system to be $(.3 \pm .15)$ photoelectrons. In all cases this noise measurement was carried out with only very little time to stabilize so the noise rates we find should be considered as upper limits to what one can achieve.

Results of Measurement: EMI9839KB

We sorted the tubes for the Cherenkov counter by demanding adequate gain and single electron resolution, eliminating tubes with excessive noise and then sorting according to quantum efficiency so that the tubes with best photocathodes are in the most important locations. In Figure 3, we see the distributions of resolution and noise rate observed for these tubes. The photocathode sensitivity measurements are shown in Figure 4. We note that the measurements of response at 3700Å and 4200Å are well correlated. Selection on blue response alone would be adequate. We compared our measurements with the manufacturers' measure of blue response (CB) and found good correlation. The combined uncertainty of their measure and ours is about 5% $\sigma$. Although our blue response numbers are relative numbers only, we have normalized them approximately to the EMI Corning Blue numbers. A Corning Blue measure of 10 corresponds approximately to a quantum efficiency of 25% at 4200Å.

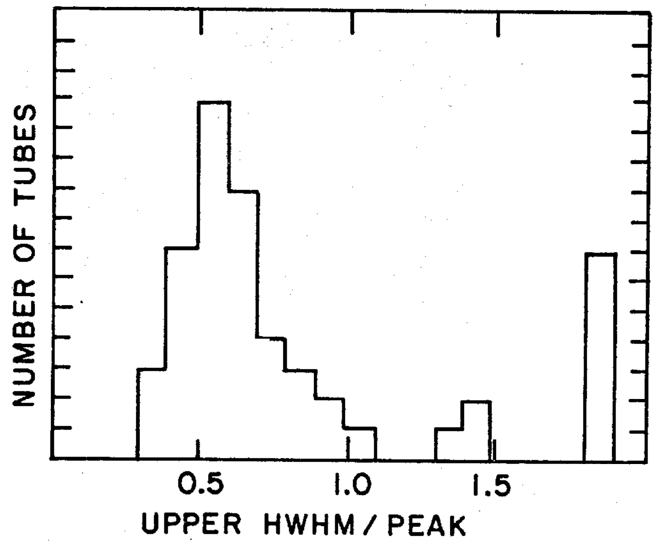



Fig. 3A. Distributions of Laboratory Measurements for EMI9839KB. Half width at half maximum / peak measured on upper side. Tubes with no discernible peak are plotted to right at 1.5.

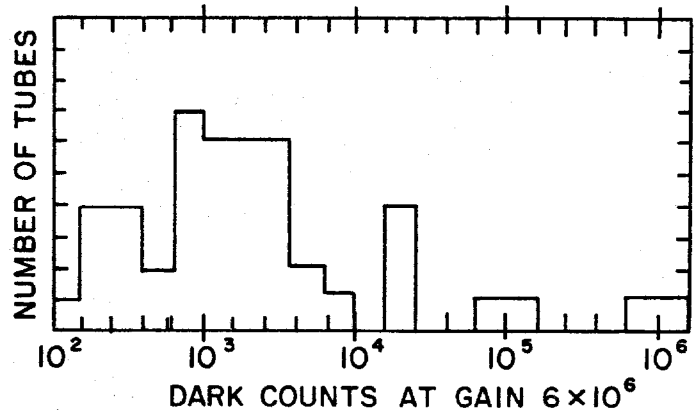



Fig. 3B. Distributions of Laboratory Measurements for EMI9839KB. Noise rate at fixed gain.

Measurements of Amperex, EMI, Hamamatsu and RCA Tubes

In addition to the large sample of EMI 9839KB tubes described we tested samples of 3 Amperex PM 2262 tubes, 2 Hamamatsu R1332 tubes and 1 Hamamatsu R1262X tube supplied by the manufacturer, as well as three RCA 8850 tubes for comparison. One of the latter was purchased recently while the other two have a history unknown to the authors.

Pulse shape data on representative tubes are shown in Figure 5. Note that all tubes have an asymmetric pulse shape with better rise than fall times. Although much effort was expended to eliminate ringing effects due to the base assembly, the small effects on the Amperex, EMI and RCA tubes may still represent basing limitations. The more severe ringing observed on the Hamamatsu R1262X tube was carefully investigated and

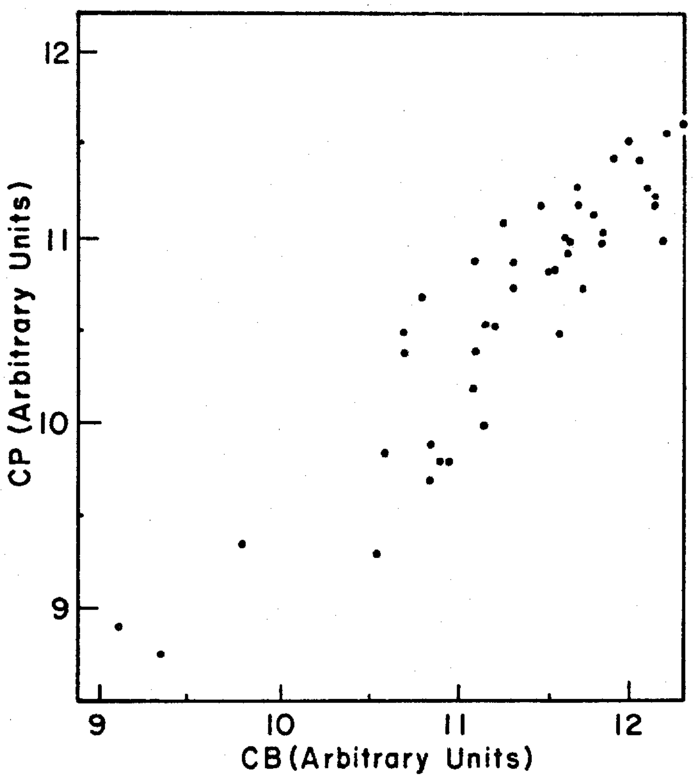



Fig. 4A. Photocathode Sensitivity Measurements for EMI9839KB. Correlation of blue (4200Å) and ultraviolet (3700Å) measurements. Both scales are arbitrary.

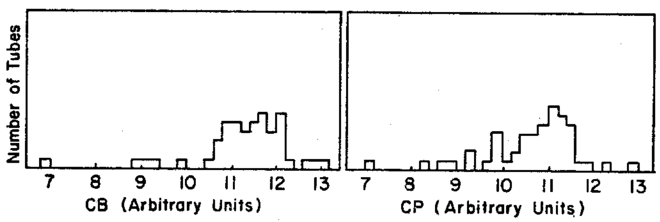
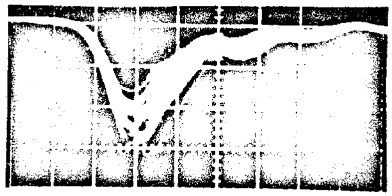



Fig. 4B. Photocathode Sensitivity Measurements for EMI9839KB. Distribution of measurements of CB and CP.

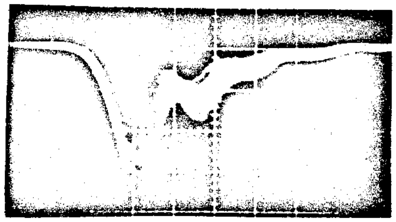
found not to be associated with the base. The manufacturer advised us that the ringing effects were believed to be associated with the anode structure.[15]

In Table II, we list other measured parameters for a few EMI tubes plus the other tubes available. The Hamamatsu R1262X tube was not available to us at the same time. Observations of its single electron resolution was made with a system with poor linearity so the FWHM was poorly measured. However we did observe multiphoton spectra with separations between 3 and 4 clearly seen. We did not optimize our light level to determine the largest number which was discernible but the multiphoton resolution of the R1262X was clearly the best of any tube in this sample. For the purpose of measuring and monitoring gain, all the tube types have adequate single electron resolution. Although we do not consider the noise measurements we have to be definitive, all tubes have rates low enough to be interesting for single photon counting. Likewise, all tubes have adequate photocathode response for Cherenkov applications. We have not performed cathode uniformity tests.

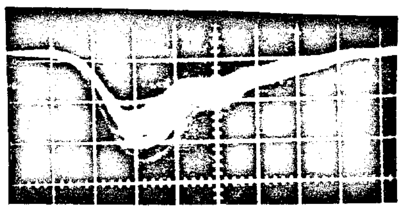
EMI Tube 9839KB #75428 — 2100 Volts, 20 mV/div., 2 ns/div.



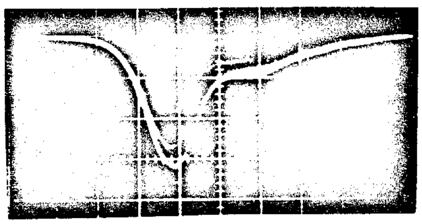
Amperex Tube PM2262 #35 — 1760 Volts, 10 mV/div., 2 ns/div.



RCA Tube 8850 #P23972 — 2200 Volts, 5 mV/div., 2 ns/div.



Hamamatsu Tube R1332 #25 — 1900 Volts, 5 mV/div., 2 ns/div.



Hamamatsu Tube R1262X — 1800 Volts, 10 mV/div., 2 ns/div.

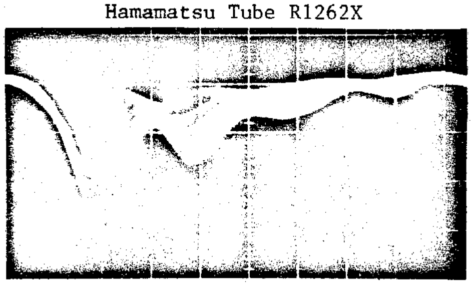


Fig. 5. Single electron noise pulses as measured by a Tektronix 7904 Oscilloscope. Refer to the cautionary notes in text.

## RESULTS OF LABORATORY MEASUREMENTS

| Tube Type | EMI9839KB | | | | HAMAMATSU R1332 | | AMPEREX PM2262 | | | RCA 8850 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Serial Number | 73200 | 75293 | 75318 | 75429 | ZC2748 | 25 | 35 | 36 | 3050 | H15426 | P23972 | C06608 |
| Photocathode | | | | | | | | | | | | |
| CB | 8.5 | 10.4 | 11.7 | 10.6 | 12.5 | 12.0 | 12.4 | 12.2 | 12.3 | 11.2 | 9.8 | 10.4 |
| CP | 7.5 | 9.8 | 10.8 | 9.9 | 11.5 | 11.6 | 12.0 | 12.0 | 11.6 | 10.1 | 9.4 | 9.7 |
| Single Electron Resolution | | | | | | | | | | | | |
| Upper | | | | | | | | | | | | |
| HWHM/Peak | .33 | .42 | .59 | .39 | .46 | .29 | .40 | .32 | .38 | .25 | .28 | .22 |
| Voltage[b] | 1760 | 1970 | 1910 | 1940 | 1940 | 1750 | 1570 | 1590 | 1660 | 1930 | 2050 | 1820 |
| Noise Counts | 2908 | 246 | 137 | 18K | 780 | 1300 | 475 | 280 | 1300 | 550 | 300 | 350 |

[b]Voltage at which gain $7 \times 10^6$ was achieved using base with linear voltage distribution.

### Multiphotoelectron Resolution

Except for possible instantaneous current effects (which we did not measure), the multiphotoelectron resolution of a tube is determined fully by the single electron distribution. For reference purposes, we have chosen three tubes for illustration of the multiphotoelectron resolution obtained with various single electron resolution widths. The light level for each test was adjusted to provide the same number of counts in each of two peaks to illustrate the maximum number of discernible peaks in such a distribution. Figure 6 shows the relevant distributions.

### Conclusions

Our most important conclusion is that now four manufacturers supply tubes with high gain first dynodes. We have examined small samples of tubes from Amperex and Hamamatsu and found them to be very desirable but of course wider variation should be expected in a large sample. With a large sample of EMI9839KB tubes we find all but a few are suitable for our use in a multicell Cherenkov counter. For our purpose, we have found no important limitation due to the plano-plano tube envelope while its use has resulted in considerable cost savings.

### Acknowledgements

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### References

*Research supported by the U. S. Department of Energy.

1. R. E. Simon & B. F. Williams, IEEE Trans. Nucl. Sci., NS-15, 167 (1968). G. A. Morton et. al., IEEE Trans. Nucl. Sci., NS-16 #1, 92 (1969). H. A. Krall et. al., IEEE Trans. Nucl. Sci., NS-17 #3, 71 (1970).

2. Cherenkov counter use previously reported includes D. D. Yovanovitch et. al., Nucl. Instr. and Methods 94, 477 (1971).

3. First use of this counter is planned for Fermilab Experiment 557 and 580.

4. E. L. Garwin et. al., Nucl. Instr. and Methods, 107, 365 (1973). P. Baillon et. al., Nucl. Instr. and Methods, 126, 13 (1975).

5. R. J. Stapleton and A. G. Wright, Nucl. Instr. and Methods, 167, 359 (1979).

6. Mirror blank was purchased from Eagle Convex Glass Company, Clarksburg, W. Virginia and vacuum deposited with Al and $MgF_2$ by Evaporated Metal Films, Ithaca, New York.

7. H. Hinterberger et. al., Rev. Sci. Instr., 41, 413 (1970). R. Winston, J. Opt. Soc. Am. 60, 245 (1970).

8. These cones were fabricated from glass cylinders by Kontes-Martin Glass Co., Evanston, Illinois, and coated with Al by Evaporated Metal Films.

9. It was found that once adequate alignment had been performed to put the light spot into the light collection cone, further alignment changes brought no enhancement of efficiency even when all the light fell directly on the photocathode. We concluded thereby that we could ignore losses due to reflection on the Winston Cone.

10. For a fuller discussion of this and related measurements see Cordon R. Kerns, "Photomultiplier Tubes", Fermilab Academic Lecture Series, May 1977 (unpublished).

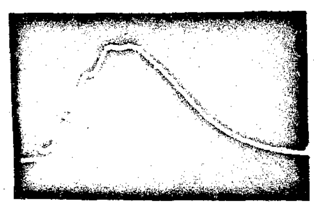
11. Corning Color Filter Glasses, Bulletin CFG, April 1979, Corning Glass Works, Corning, New York 14831.

12. EMI Photomultipliers Catalog, 1979, page 2.

13. I. Berlman, Handbook of Fluorescence Spectra of Aromatic Molecules, 2nd Edition, Academic Press, New York, 1971, page 220.

14. Gain measurements could also be made using the chopped light source. One begins in a photodiode mode for normalization. See reference 10. The two techniques are in reasonable agreement.

15. Private Communication.



Four Peaks

RCA 8850

#C066080

$\frac{\text{HWHM}}{\text{PEAK}} = .213$

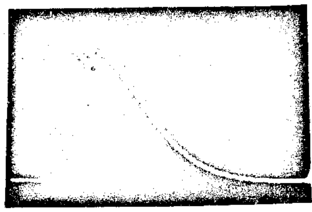
Fig. 6A.

Three Peaks

Amperex PM2262

#3050

$\frac{\text{HWHM}}{\text{PEAK}}$ = .375



Two Peaks

EMI 9839KB

#75417

$\frac{\text{HWHM}}{\text{PEAK}}$ = .48

Fig. 6B & 6C. Multiphotoelectron Pulse Height Spectra (counts vs. pulse height). Light levels were chosen to illustrate maximum resolvable number of photoelectrons.